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Thermal Protection System Technologies for Enabling Future Mars/Titan Science Missions

by

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INTRODUCTION

This NRC Decadal Survey white paper, provided by the thermal protection technology community, is a general assessment of current capabilities as well as gaps in the thermal protection systems (TPS) technologies that support Mars missions[1-4]. The paper begins with a brief history of TPS relevant to the exploration of Mars and is followed by a discussion of current TPS capability and technology issues. It concludes with recommendations for a TPS Technology Program that includes the research, development, testing and manufacturing capabilities needed to meet potential Mars and Titan mission requirements.

BACKGROUND: Historical Overview of TPS Development

For vehicles traveling at hypersonic speeds in an atmospheric environment, TPS is a single-point-failure system. TPS is essential to shield the vehicle and the payloads and crew against the high aerodynamic heating encountered during (re-)entry. It enables the safe deployment of *in-situ* science instruments using probes, landers, balloons and other instrumented systems. Minimizing the weight and cost of TPS while ensuring the integrity of the vehicle is a continuing challenge for the TPS community.

The origin of thermal protection systems can be traced back to the technological efforts to perfect ICBM's. Without an effective TPS, the nuclear warheads would not survive the heating during the descent phase. Early missile designs had sharp pointed noses and consistently failed during reentry due to the high heating and lack of a suitable TPS material. Viable reentry vehicles became possible after two innovations: 1) the blunt body concept proposed by H. Julian Allen at the Ames Aeronautical Laboratory and 2) ablative TPS. Essentially, the blunt body concept coupled with ablative materials was designed to deflect, reject, and reradiate the heat load - not absorb it. President Kennedy's call in 1961 for Lunar Landing within a decade and the national defense needs to improve ICBM accuracy resulted in a massive investment in ablative TPS development and significant advances were made in this period.

NASA and U.S. Military mission requirements led to a rapid development of practical ablative thermal protection materials. Carbon- or silica-based materials infused with phenolic-resin composites proved to be the most suitable candidate materials for many missions. Silica-based systems were found to be more efficient at lower heat fluxes (or lower entry speeds) due to their lower thermal conductivity. Carbon-based systems, with their much higher temperature capability, were more suitable for higher heat flux entries.

Two other critical components in the development of viable thermal protection systems in the 1960s were 1) the development of hypersonic ground test facilities including arc jets, shock tubes, and ballistic ranges and 2) the development of analytical models and codes that predict the aerothermal environment during entry (both convective and radiative) and the thermal and ablation response of candidate TPS materials.

During the 1960s and into the mid-70s, the ablative TPS community in the U.S. was very active. By the late 1970s, the research, development, and testing of ablative TPS materials significantly declined as the nuclear missile programs were completed and the Apollo program was terminated after several successful moon landings. NASA shifted its focus to the Space Shuttle program which was designed to be a reusable system. While

reusable TPS research, development and testing occurred in the late 1970s and through the 1980s, the ablative TPS community saw a serious decline in capability.

However, NASA continued to require ablative TPS for an occasional robotic entry probe mission, e.g., Mars Viking, Pioneer-Venus, Galileo. Fortunately, TPS requirements for these missions were satisfied with existing ablative materials. In particular, NASA took advantage of the significant investment made by the U.S. military in the 1970s in developing FM5055 carbon phenolic for use as heat shields on ICBM reentry vehicles. Since then, NASA and industry have made modest investments in ablative TPS in support of specific missions.

Mars Exploration from a TPS Perspective

TPS designers at Lockheed Martin (LM), adapting the Apollo TPS honeycomb architecture, developed a silica-based, lightweight ablator that could be hand packed into a glass-phenolic honeycomb. This was called the Super Lightweight Ablator (SLA), which has been used in all NASA Mars missions from Viking to Phoenix. Thirty years later, when Mars Pathfinder (MPF) needed a TPS, LM recovered the SLA processing capability. In 2005, the MSL project selected SLA as the TPS and proceeded to design the aeroshell. As a direct consequence of TPS failures during arc jet testing, the MSL project had to switch from SLA to Phenolic Impregnated Carbon Ablator (PICA) after the Critical Design Review. The switch from SLA to PICA was possible only because of development investments already made by the Orion TPS project. This was a prime example of how NASA's TPS community can work together and co-develop materials and technology that can benefit multiple projects and programs. This is also an example of fortunate happenstance rather than a planned risk mitigation strategy. **One *very* important lesson learned in this process was that several years of intense and expensive can be required to implement even modest TPS improvements**, particularly if the core skillsets have been allowed to erode. Maintenance of the critical specialized skillset in NASA and industry is necessary to ensure that the agency is capable of meeting future mission requirements.

Titan Exploration from a TPS Perspective

Titan missions are relatively easier due to the dense Titan atmosphere and lower relative entry velocities. Entry conditions are similar to Mars. The Huygens mission success has demonstrated this well. The European Space Agency (ESA) was successful in designing a heat shield[5] with AQ60, which is similar in performance to SLA-561V. During design and after launch, the TPS design community debated about the anticipated heating due to the uncertainty of the percentage of methane in the Titan atmosphere which is composed mainly of nitrogen molecules and a small percentage of methane. The successful spectroscopic measurement of methane by Cassini-Huygens coupled with the research efforts of the US and ESA teams led to greater understanding of the Titan entry.

CURRENT TPS CAPABILITY

Table 1 lists the peak stagnation point entry conditions for representative robotic Mars and Titan missions[(1-4)]. Obviously, individual aeroshell shapes and weights, orbits and trajectories, entry speeds and angles will affect the actual entry conditions for each mission. From a TPS perspective, Mars missions range from the fairly benign environment of an entry from orbit, e.g., Viking, to the more demanding lifting entry, e.g.

Table 1. Stagnation point environments: Mars and Titan mission materials

Heat Shield Peak Stagnation Conditions	Mars Missions					Titan Missions	
	Viking-Like (Orb. Entry)	Ballistic (MPF - Pheonix)	Lifting (MSL class)	Aero-capture	Earth Entry (Mars Return)	Ballistic (Huygens)	Aerocapture
V_e (km/s)	4.42	(5.5 – 7.2)	(5.7-5.9)	~7.2	~(10.8 – 12.6)	6.0	6.0
$\dot{q}_{convective}$ (W/cm^2)	21	(44 – 105)	~200	(57 – 112)	~(750 – 942)	50	~60
$\dot{q}_{radiative}$ (W/cm^2)	0	(0 – 5)	~0	~0	~(0 – 150)	(15- 45)	~40
$\dot{q}_{combined}$ (W/cm^2)	21	(44 – 110)	~200	(57 – 112)	~(750 – 1100)	(65-95)	100
$Q_{combined}$ (kJ/cm^2)	~1	~4	~6	(5.5 – 12.0)	(16 – 36)	4	20
$p_{stagnation}$ (atm)	0.06	< 0.2	< 0.4	<0.2	(0.3 – 0.4)	0.1	0.1
Arc jet simulation (Air)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Arc jet simulatio in actual gas composition	No CO_2	No CO_2	No CO_2	No CO_2	Yes	(N2-CH4) Feasible	(N2-CH4) Feasible

MSL, and aerocapture type missions, which experiences much greater heat load. The most challenging of future Mars missions is Mars Sample Return (MSR), which may include a landed mission element followed by a return of the sample to Earth. Current

Table 2. Candidate ablative heat shield TPS materials for Mars and Titan

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit: Heat flux, W/cm^2	Potential Limit: Pressure atm	Entry at Mars: MPF Class	Entry at Mars: MSL Class	Entry at Mars: Aero-capture	Earth Return‡	Titan: Direct	Titan: Aero-capture
FOREBODY HEAT SHIELD											
Low-Mid	SLA 561V	LMA	Mars	< 120 (<300)*	< 1	●	✖	◡	✖	●	●
	PICA	FMI	Stardust	~ 1200	< 1	■	●	●	✖	●	●
	BPA	Boeing	TRL 3-4	~ 1000	~ 1	■	◡	◡	✖	◡	◡
	Avcoat	Textron	Apollo	~ 1000	~ 1	■	●	●	✖	●	●
	AQ60#	EADS	Huygens	~ 250	< 1	◡	✖	◡	✖	●	◡
	Acusil® II†	ITT	DOD MSL	100	< 1	✖	✖	◡	✖	◡	◡
	SRAM Family	ARA	TRL 5-6	~ 300*	~ 1	◡	◡	◡	✖	◡	◡
	Lower density Phen-Carb	ARA	TRL 5-6	< 2000	~1	■	◡	◡	✖	◡	◡
Mid	ACC	LMA/C-Cat	Genesis	> 2000	> 1	■	■	■	✖	■	■
	Mid-density PhenCarb	Several	TRL 4-5	~ 2,000-4000	> 1	■	■	■	✖	■	■
High	3DQP	Textron	DOD	~ 5000	> 1	■	■	■	✖	■	■
	Heritage Carbon phenolic	None today but several can	Venus, Jupiter	10,000-30,000	>> 1	■	■	■	●	■	■

● Fully capable ◡ Potentially capable, qual needed ■ Capable but heavy ✖ Not capable

†RF transparent #European Supplier * (heat flux limit is lower with high shear, higher at low shear)

Note: Reliability requirements for MSR EEV can only be met by heritage carbon phenolic TPS

mission planning for MSR assumes the MSL technology, including TPS, will be sufficient for the landed element. The sample return mission is similar to the successful Stardust mission except for the reliability requirement. MSR mission design has to meet the planetary protection requirements that dictate a reliability of 0.999999 or the probability of failure of no more than 1 in a 1,000,000.

The last two columns in Table 1 include representative Titan missions based on ballistic entry and aerocapture trajectories. While the Titan entry conditions such as maximum heat flux and pressure are comparable to the range of Mars relevant conditions, the heat load is considerably higher for Titan aerocapture. Although we do not provide the conditions for back shell, we can establish upper and lower estimates (2% - 10% of stagnation point values). Although the MSR and Titan Aerocapture missions are not anticipated to take place in the next decade, technology readiness, especially for TPS, is required to enable these missions in the following decade.

Materials

TPS for an entry capsule design typically incorporates several materials, each selected based on the environmental requirements and their associated uncertainties while striving to minimize total TPS mass. Tables 2 and 3 provide a representative set of heatshield and backshell TPS materials, their potential performance limits, and potential applicability for Mars and Titan missions. In selecting the TPS for the backshell, in addition to heating requirements, RF transparency and Reaction Control System (RCS) jet interaction may need to be considered. The requirements for the TPS for MSR Earth Entry Vehicle (EEV) are driven by the planetary protection requirement, i.e., a failure rate of less than one in a million. The only TPS that currently meets the reliability requirement is the heritage carbon phenolic. It is possible, depending on the continued successful use of Avcoat for human missions prior to MSR, that Avcoat could be a viable candidate. However, insufficient flight data exists on the current generation of Avcoat, which is still undergoing qualification for the Orion heat shield. Thus, only heritage carbon phenolic is viable and a fully capable candidate for Mars Sample Return mission. **A *very* important lesson learned by MSL is that it is wise to have at least two viable candidate TPS materials in place for mission projects**, because shifting mission requirements or unanticipated failure modes may invalidate one or more of the options.

Table 3. Candidate ablative back shell TPS materials for Mars and Titan

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit		Mars Direct		Mars	Titan	
				Heat flux, W/cm^2	Pressure atm	Size ~MPF	Size (MSL)	Aero-capture	Direct	Aero-capture
BACKSHELL TPS										
Low	SLA-561V*	LMA	Mars	< 120 (<300)*	< 1	●	●	●	●	●
	SRAM Family	ARA	TRL 5-6	~ 300	~ 1	◡	◡	◡	◡	◡
	AQ60	EADS	Huygens	~ 250	< 1	◡	◡	◡	●	●
	SIRCA†	Ames	Mars	~ 150	> 1	◡	◡	◡	◡	◡
	Acusil® II†	ITT	DOD MSL	100	< 1	●	●	●	●	●
	SLA-561S	LMA	Mars	< 20	< 1	●	✖	✖	◡	✖

● Fully capable ◡ Potentially capable, qual needed ■ Capable but heavy ✖ Not capable

†RF transparent #European Supplier * (heat flux limit is lower with high shear, higher at low shear)

Ground Test Facilities

A mainstay of TPS development for the past several decades has been the high-power arc jet facilities at ARC, JSC, AEDC, and Boeing (LCAT). These facilities, with power capabilities from 10 to 60-MW, provide the largest test article and have the highest available heating capability. The arc jets have proven to be indispensable for TPS development work as well as certification of flight hardware[6].

Current test capability limitations for Mars and Titan missions fall into three categories: 1) the inability to provide combined convective and radiative environment, 2) the inability to test in gas composition for Mars and Titan and 3) the inability to reproduce flight environment effects in ground test facilities.

To provide combined convective-radiative heating test environment, CEV project is developing a design for a new act jet facility. To provide appropriate test gas composition for Mars and Titan, NASA is evaluating the challenges of converting the workhorse facilities, AHF at Ames and TP2 at JSC, to run on CO_2 or N_2/CH_4. While feasible, these modifications will require resources and time. Ames is close to completing a Development Arc jet Facility (DAF), which is a smaller facility with the possibility of operating on a wide variety of gas mixtures, including CO_2 and N_2/CH_4. DAF will consume a fraction of the power needed by larger facilities, making test exposures of four hours or longer and repetitive sample exposures possible. However, assembly of this facility has been delayed due to a lack of adequate financial resources and mission drivers. To reproduce flight environment effects, improvements in technical engineering development must be made so that design of experiments, facility characterization, improved physical models for the relevant TPS-aerothermal processes, and improved leveraging of historical test data become available.

Technical Engineering Development

Validated aerothermal environments and material response models, including associated uncertainties, are needed for the overall TPS design for flight. These models are validated primarily using ground based test data and they extrapolate the ground test results to the flight environment. Ablating TPS is an inherently coupled problem, requiring detailed understanding of the environment/TPS interactions. Inadequate models can lead to increased mass, reduced reliability, and in the worst-case possible undetected failure modes in the TPS system. Recent lessons learned from MSL and CEV TPS design point to deficiencies that we need to over come.

RECOMMENDATIONS

If maintained, the TPS materials, tools, and test facilities available and in use today can meet the requirements for the anticipated Mars and Titan missions over the next decade.

For the Scout, Discovery and New Frontier Class missions, the cost cap and risk posture require the use of off-the-shelf TPS. Improvement in materials development, ground test facilities, and technical engineering could significantly benefit Mars and Titan missions in terms of decreased mass, increased reliability, and/or reduced manufacturing costs. At present, NASA does not have a dedicated TPS Technology Program to ensure continued availability of capable TPS, nor is it able to support improvements . Instead, NASA relies on industry to provide the TPS when needed. However, industry faces significant

business challenges in meeting this need due to uncertainties in NASA programs and missions. ***This represents a significant risk to NASA missions requiring TPS.***

NASA anticipates flying MSR and Titan Flagship missions in the decade following 2022, and the risks to these missions are even greater. The risk to the Titan mission will be easier to manage if NASA develops and manages a process to ensure availability of capable TPS in the coming decade.

This is not the case for MSR EEV. Heritage carbon phenolic, the only material that meets the TPS requirements, is not currently in production, nor is the needed precursor, Avtex rayon. The limited supply of heritage rayon that NASA Ames has secured is estimated to be large enough for only two missions requiring high performance heat shields and could be quickly used by other planetary missions during the next decade. There are alternatives to heritage rayon, and many vendors are capable of manufacturing the heritage as well as alternate carbon phenolic, if they are provided with the heritage manufacturing process. The challenge will be to develop and prove the capability of the alternate carbon phenolic, an effort that will require both time and resources.

The more beneficial risk mitigation strategy would be to establish and support a broader TPS Technology program to take advantage of advances in material science in the last two decades and past investments by In-Space Propulsion program, Orion and MSL. With this type of cross-cutting, sustained program in place, interest in the development and manufacturing of attractive and alternative TPS materials and architectures would be rekindled and have the potential to be mass efficient, more reliable and cost less.

The completion of DAF, conversion of larger AHF and TP2 to operate on CO_2 or N_2/CH_4, and the development of the new bay will close the present facility gap in testing. Improved testing methodologies combined with validated analytical methods will reduce the risk of qualifying and certifying TPS materials for Mars and Titan.

Current ablative TPS designs are still using methodologies and tools developed in the 60s and 70s. One major problem has been the impossibility of validating the models with flight data because flight instrumentation on reentry probes has not been used since Apollo. Galileo was an exception. If successful, the MSL mission will provide needed data about the performance of PICA at Mars. Lack of flight data has led to TPS designs that are conservative and therefore heavy. When considering that mass savings in TPS could be applied to additional scientific instrumentation, it is evident that more effort needs to be expended to improve TPS design methodologies. Combined with modest investments in analytical tools and models, TPS systems could achieve significant weight reduction without any performance degradation.

Specifically it is recommended that NASA establish a cross-cutting TPS Technology program with elements focused on sustaining current technologies, and elements focused on enabling future Mars Sample Return and Titan missions. The program will need to focus on the following:

Materials:

1. Sustaining current material manufacturing capabilities and expertise to ensure that at least two proven materials, for both the heat shield and backshell, are available. Recertification or qualification of these materials needs to occur every few years
2. Fully recovering the heritage manufacturing process for carbon phenolic material

3. Developing alternatives to carbon phenolic materials using currently available precursors or further developing and qualifying mid-density ablative materials.

Technical Engineering Development:

Improving design and analysis tools, such as aerothermal CFD, material response models, and the coupling between them to reduce uncertainties in the flight environment as well as verify material response and qualification test conditions. These improvements will also aid in analyzing material reliability concerns.

Arc Jet Facilities:

Ensuring NASA has arc jet facilities capable of testing in CO_2 and N_2/CH_4

Flight Instrumentation:

Including TPS instrumentation on all future NASA Mars and Titan missions in order to generate a database of relevant flight data, which will aid in reducing the risk to and improving the performance of future missions.

In conclusion, TPS Technologies for Mars and Titan missions are NASA unique, and challenging. They require specialized resources in terms of expertise, facilities and capabilities across NASA and Industry. These can be deployed to support all appropriate NASA missions. The Decadal committee needs to consider the specific recommendations made above. The TPS needs for other Science destinations addressed in companion TPS white papers and the needs of other NASA stakeholders must also be addressed to ensure the taxpayer dollars provide the maximum return on investment.

Finally, it is requested that the new Decadal planning team give the TPS community timely feedback on those missions that emerge as high priority and involve atmospheric flight. With this feedback, we can focus our recommendations as appropriate to those missions and, if helpful, we can also provide cost and schedule estimates upon request.

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